Original articles

J. Perinat. Med.
14 (1986) 391

Techniques for the routine on-line processing of the fetal electrocardiogram

Derrick L. Kirk and Peter R. Smith

Department of Electrical and Electronic Engineering, The University of Nottingham, U.K.

1 Recovery of the FECG from noise

Since CREMER's [1] first observation of the fetal electrocardiogram (FECG) there have been many attempts at using the FECG to characterize the well being of the fetus during labor, particularly with regard to the degree of acidosis that may exist within the fetus. To do so in a meaningful manner, requires a well resolved FECG waveform in which the P, QRS and T wave components are clearly defined. The FECG is usually obtained from a simple scalp electrode used in conjunction with an indifferent electrode. The waveform is immersed in low frequency biological noise arising from nerve responses and muscle movements. Noise is compounded with artifacts (brought about by maternal or fetal movement), maternal ECG signals, mains 50 Hz pick up, polarization effects at the electrode-scalp interface and fetal EEG signals. Figure 1 presents a characteristic signal obtained from a conventional scalp electrode. The QRS component is the only clearly resolved component of the FECG waveform.

In the past, various techniques have been used to enhance or recover the FECG from noise. The technique of computing of averaged transients was used by HON and HESS [2] in order to improve the signal-to-noise ratio of the FECG waveform. However, this form of enhancement procedure also suppresses the effects of any short term transient phenomena occurring within the FECG waveform. A moving window averaging process has been used by RHYNE [3] to recover the FECG from noise. He employed an algorithmic process, operating upon dedicated hardware. SCOTT [4] went on to show that the algorithm used by RHYNE was in essence a recursive digital filter. Work by SHEILD and KIRK [5] went on to apply the techniques of digital filtering to the recovery, during labor, of the FECG from noise. Optimized digital filters, matched to the frequency spectrum of the FECG waveform, were defined in this previous work [5]. In the current study similar

Curriculum vitae

DERRICK L. KIRK, *B.Sc., ARCS, DIC, Ph.D., graduated in Physics from Imperial College London in 1964. He was awarded a Ph.D. in Metallurgy also from Imperial College in 1967. This was followed by a three year period at the Clarendon Laboratory, Oxford. In 1970, he was appointed Assistant Lecturer in the Department of Electrical and Electronic Engineering at the University of Nottingham. During his period of time at Nottingham, he has initiated research work in Solid State Devices and Digital Signal Processing. In 1981, he was made a titled Reader in Applied Physical Electronics.*

© 1986 by Walter de Gruyter & Co. Berlin · New York

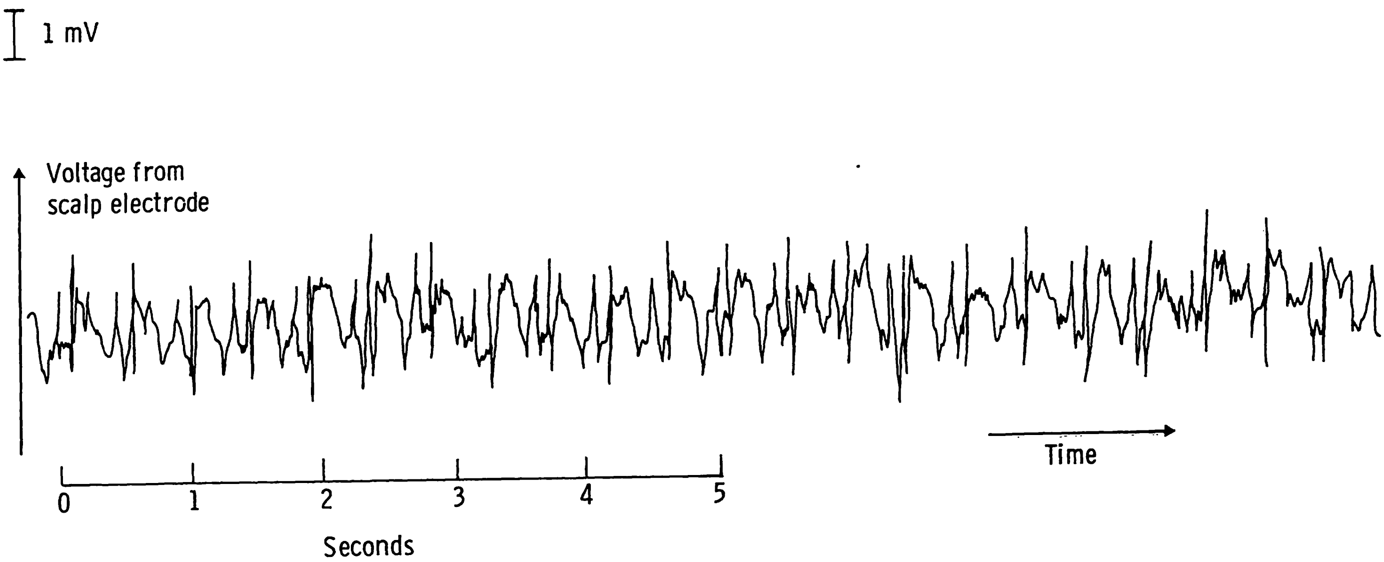

Figure 1. Voltage-time trace as obtained from a simple scalp electrode.

digital filters have been implemented upon a DEC 11-23 processor and hard disk system.

The manner of processing of the FECG is depicted in figure 2. In this system, a 12 bit, 16 channel A-to-D converter samples both FECG and variations in intra uterine pressurer (IUP). The sampling rates are respectively 500 Hz and 1 Hz for the FECG and IUP signals obtained from the respective transducers. The digitized FECG waveform is stored in an input ring buffer. Software routines search for the QRS complex and align the complex within the ring buffer. The software processing also evaluates the fetal heart rate and the noise content of the signal. Following alignment, four FECG waveforms are summed in a buffer. The summed waveform is recovered from noise with time coherent filtering which effectively produces a weighted moving average of the most recently detected complexes. At 15 second intervals, the current output of the coherent filter is presented for evaluation of the various parameters of the FECG waveform. Software fitting routines measure some 18 different parameters of the FECG complex. These are presented, along with the FECG waveforms recovered from noise, upon an Apple II microcomputer with graphics display. The parameters associated with the complex can also be stored upon a disk system along with other clinical information and data.

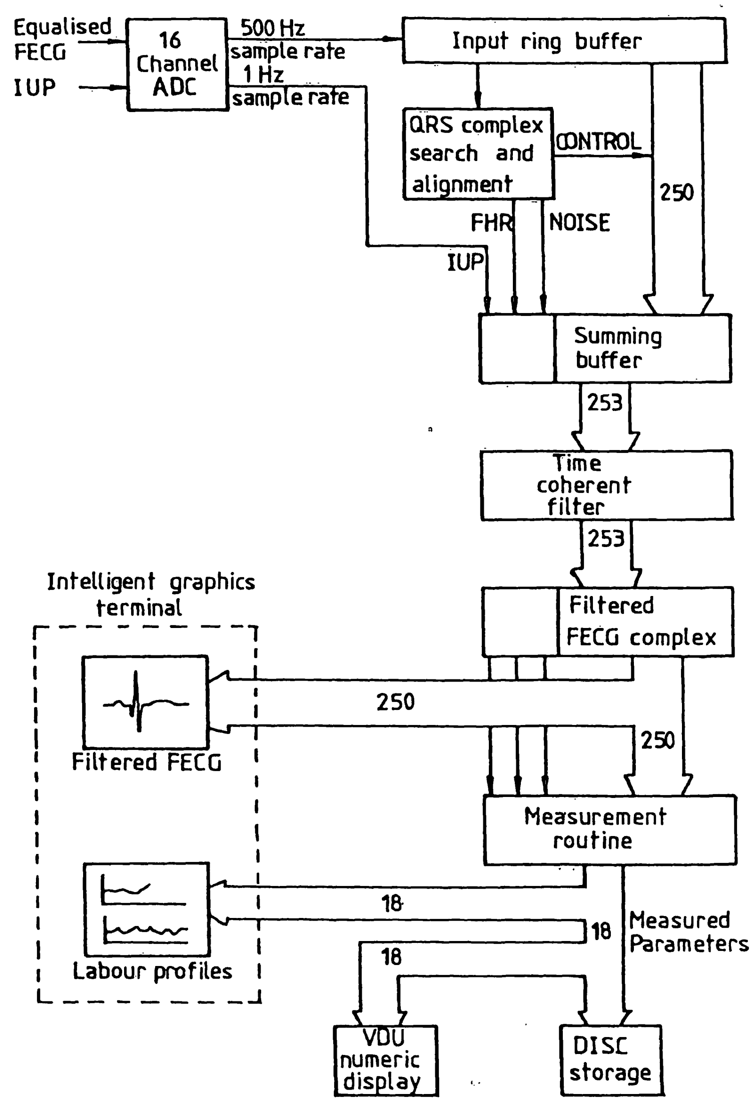

Figure 2. The processing of the FECG waveform. The numbers indicate the number of bits allocated to a particular data stream.

2 Processing of the FECG waveform recovered from noise

As stated, the FECG waveform that had been recovered from noise, was processed by a software measurement routine at intervals of 15 seconds. This ensured adequate time resolution of changes occurring during labor. Search ranges were defined for each wave component of the FECG. Within these ranges, a point having maximum or minimum amplitude is temporarily defined as the peak of a particular wave component. The P, Q, R, S and T waves are identified in this manner. Table I identifies the limits of the search ranges utilized in the processing software.

A linear model of the FECG was then formed by software (figure 3). A series of linear elements was constructed through the sampled points forming the FECG waveform. The technique of linear regression was then used to obtain the best fit between the linear model and the FECG waveform. Then, for a given FECG

Table I. FECG wave component search ranges.

Wave component	search range (ms)	
	From →	To
R*	190	210
Q	R − 26	R − 6
S	R + 6	R + 26
P	R − 140	R − 60
T	R + 70	R + 210

* Note the R search is relative to start of the buffer containing the digitized FECG waveform. Subsequent searches are relative to this R wave location.

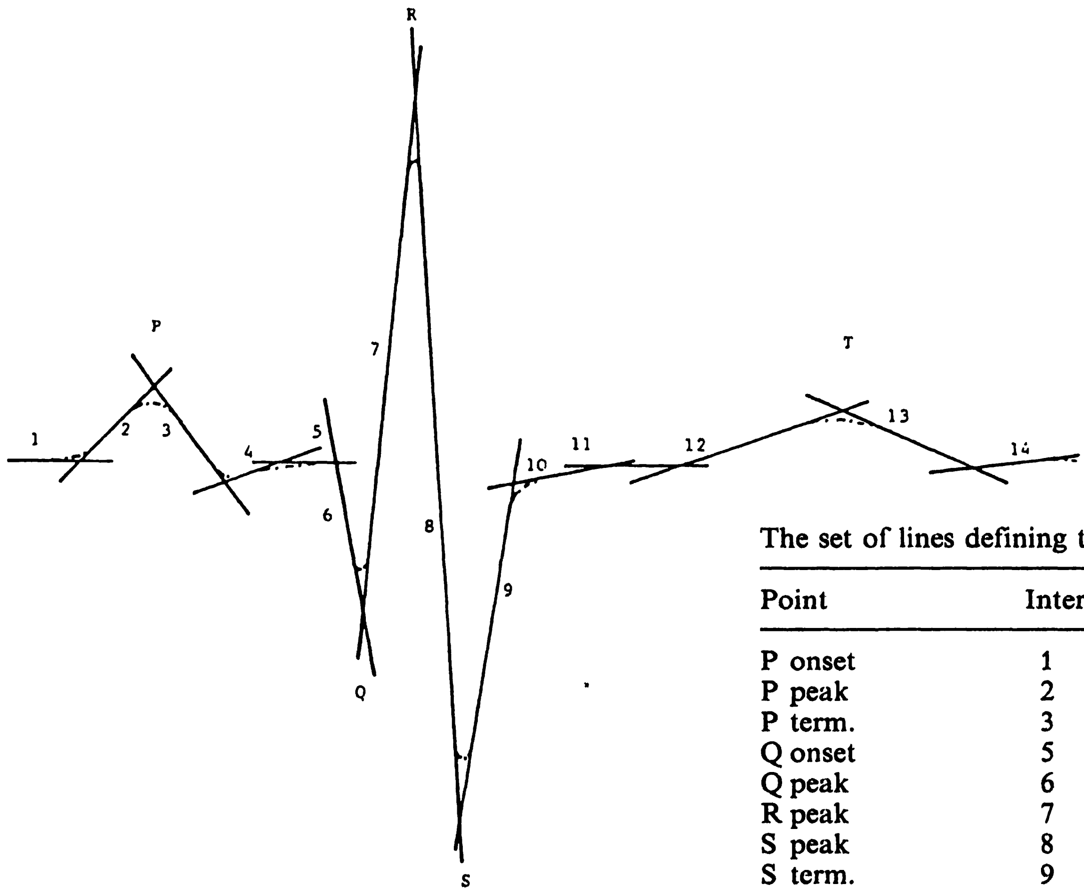

Figure 3. The linear model of the FECG used to analyze the waveform.

The set of lines defining the FECG waveform

Point	Intersection of	with
P onset	1	2
P peak	2	3
P term.	3	4
Q onset	5	6
Q peak	6	7
R peak	7	8
S peak	8	9
S term.	9	10
T onset	11	12
T peak	12	13
T term.	13	14

Points defined by line intersections.

Table II. Parameters measured by the system.

Abbreviation	Parameter
1 FHR	Fetal heart rate
2 IUP	Intra-uterine pressure
3 NOISE	Noise level
4 SIGNAL	Signal level
5 S/N	Signal-to-noise ratio
6 P-R	P (peak) to R (peak)
7 P(D)	P duration – P (onset) to P (term.)
8 P(A)	P area
9 Q′-R	Q (onset) to R (peak)
10 Q-R	Q (peak) to R (peak)
11 R-S	R (peak) to S (term.)
12 R-S′	R (peak) to S (term.)
13 R-T	R (peak) to T (peak)
14 T(D)	T duration – T (onset) to T (term.)
15 T(A)	T area
16 T(H)	T height
17 ST(E)	ST segment elevation
18 R/S	R-to-S ratio

wave component a line having maximum positive, or negative gradient was taken to represent the rising or falling edge of that wave component. Intersections of these edges gave peak or minima locations. To find the onset and termination of P and T waves, the optimized series of straight lines was employed. From these sets of lines, those lines having the maximum value of gradient opposite in sign to that of their neighboring falling or rising wave edge, were taken to represent the base lines either side of the wave component. The intersection of the base lines with the rising and falling edges gave the wave boundary. The base line sections associated with P onset and S wave termination were found in a similar manner. Using the linear model, the FECG time intervals of table II were calculated. The signal strength was derived from the amplitude of the QRS complex by the relationship:

$$\text{SIGNAL} = (\text{R} - \text{S})/2 \quad \text{or} \quad \text{SIGNAL} = (\text{R} - \text{Q})/2 \tag{1}$$

whichever is the greater and where R, S and Q are the amplitude values of the wave components. The FECG waveform recovered from noise is relatively noise free whilst the "raw" unprocessed waveform consists of signal plus noise. An indication of the noise level was calculated as the difference between the two:

$$\text{NOISE} = \sqrt{\sum_{i=1}^{i=250} (Y_r(i) - Y_e(i))^2} \tag{2}$$

where $Y_e(i)$ is the i'th element of the FECG waveform recovered from noise and $Y_r(i)$ is the ith element of the raw unprocessed waveform.

The following amplitudes and areas of the wave components were also evaluated by the system.

P and T wave area P(A), T(A): The area under the P and T waves was defined as the area enclosed between the wave and its base line. Limits of evaluation were set by the onset and termination of the wave. The base line on the wave was the mean of a short section of the FECG just before the onset of the wave and another section just after the termination of the wave. Areas were defined thus:

$$\text{Area} = \sum_{i=W_o}^{W_t} |Y(i) - \text{Base}| \times \frac{50}{\text{SIGNAL}} \tag{3}$$

W_o = wave onset
W_t = wave termination
$Y_{(i)}$ = amplitude of i'th wave sample
Base = level of wave's base line, calculated as follows:

$$\text{Base} = \frac{1}{16}\left|\sum_{i=A}^{A+7} Y(i) + \sum_{i=B}^{B+7} Y(i)\right| \tag{4}$$

where A is a point 30 ms before the onset of the wave component and B is a point 14 ms after the termination of the wave component. The isoelectric line was defined as the mean value of a short section of the FECG baseline just before the Q wave onset.

Height of T wave T(H): T wave height was computed as the height of the T wave peak above the base line, expressed as a fraction of the R wave height. The value used for the T wave peak is the mean of a short section of the

FECG centred around the time location of the peak. The T wave baseline was calculated as for T(A):

$$T(H) = (\text{Peak} - \text{Base}) \times \frac{1000}{R_h} \tag{5}$$

where

Base = amplitude of T wave base line, as defined previously
R_h = height of R wave over the isoelectric line
Peak = amplitude of T wave peak, calculated as follows:

$$\text{Peak} = \frac{1}{9} \sum_{i=A}^{A+8} Y(i) \tag{6}$$

where A is a point 8 ms before the T wave peak.

S-T elevation ST(E): The S-T segment is a section of the FECG base line between the S wave termination and the T wave onset. The relative height of this segment over the isoelectric line, expressed as a proportion of the R wave height is the S-T elevation.

$$ST(E) = (ST - ISO) \times \frac{1000}{R_h} \tag{7}$$

where,

R_h = height of R wave over isoelectric line
ST = amplitude of ST segment calculated as follows:

$$ST = \frac{1}{8} \sum_{i=A}^{A+7} Y(i) \tag{8}$$

where, A is a point 16 ms after the S wave termination

ISO = location of isoelectric line calculated as follows:

$$ISO = \frac{1}{10} \sum_{i=B}^{B+9} Y(i) \tag{9}$$

where B is a point 40 ms before the Q wave onset.

R-to-S wave ratio (R/S): The R/S wave ratio is the R wave height divided by the S wave height. These heights are measured relative to the isoelectric line:

$$R/S = \frac{(R - ISO)}{(ISO - S)} \times 10 \tag{10}$$

where R and S are amplitude values of the wave peaks.

ISO = location of isoelectric line, as defined previously.

The amplitude measurements were in arbitrary units scaled to give a convenient range. Where applicable a conversion factor would allow absolute voltage values to be calculated. The parameters expressed as a proportion of the R wave height were scaled so that the R wave height was equivalent to 1000 units.

At all stages throughout the enhancement and measuring routines, software checks were provided to ensure the validity of the results. These checked for and removed artifacts generated by fetal or maternal movement.

3 Data processing and display — the intelligent graphic terminal

Presentation of the large amounts of data in a format that could be readily understood, dictated the use of graphics. An Apple II microcomputer was programmed to act as an intelligent graphics terminal. This was achieved by the use of a machine code-interrupt driven routine, activated each time new data was received from the DEC computer. The routine permitted the selection of a number of alternative displays of information. The graphical displays displayed by the machine were of two forms:

(a) The presentation of an enhanced FECG waveform with markers indicating the timing points located by the measurement routine (figure 4). Also included on this display were numerical values for six user selectable parameters.

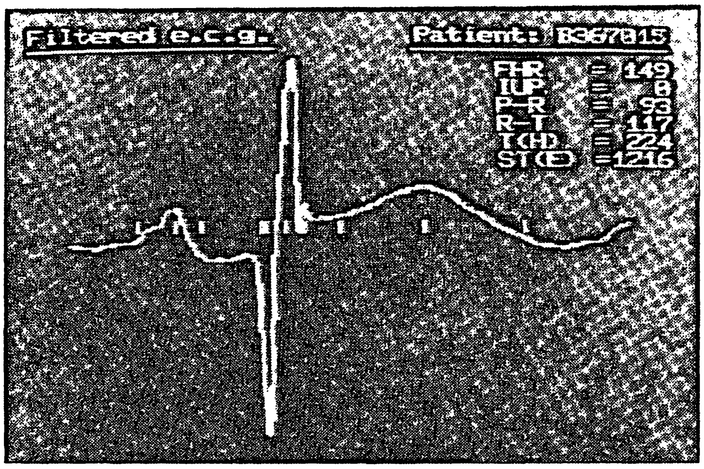

Figure 4. The FECG waveform recovered from noise.

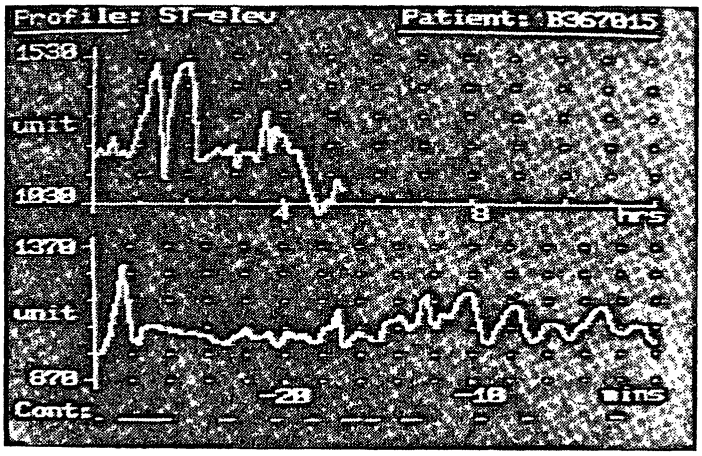

Figure 5. The time dependent variations of certain selected parameters of the FECG.

(b) Selection of any one of the 18 measured parameters of the FECG for a display that showed the long term variations of a selected parameter over a 12 hour period (figure 5). This was combined with a display of the short term variations over a 30 minute period with the location of contractions as a reference marker (figure 5). The enhanced FECG with measurement markers permitted the clinician to monitor the signal recovery and measurement processes. Variations in the shape of the FECG waveform and other more subtle attributes could be readily observed. The program also offered other facilities including selection of a command reference page and the storing of data on a floppy disc either when instructed by the user or automatically at the end of labor.

Retrospective analysis and hard copy was also obtainable from the DEC system. The labor profiles of any four selected parameters could be printed out along with IUP for the duration of the whole labor. The leader for the hard copy identified the data file number and the sampling interval of the measurements.

It was also possible to generate a numerical examination of the computed parameters. Data compression was achieved by calculating the mean and standard deviation of each parameter at selected intervals during the course of labor. These intervals were user selectable between 1 and 60 minutes.

4 Conclusions

A system capable of enhancing and processing the fetal electrocardiogram routinely, during labor, has been developed and made operational within a labor suite environment. The system operates through software running upon DEC 11-23 hardware. The equipment has been utilized by clinicians for some two years, and is establishing a base of clinical data from which patterns of behavior for both healthy and acidotic fetuses will be derived.

Summary

In order to routinely monitor the fetal electrocardiogram (FECG), during labor, in an on-line real-time situation, the following processes need to be undertaken:

1. The FECG signal must be recovered from noise.
2. The recovered signal or waveform must be measured with a high degree of precision in order to generate the timing intervals, areas and parameters that are of interest to the clinician.
3. The FECG and measured parameters must be presented to the clinician in a meaningful and simple format.
4. Control of the machine and its processing should be a user friendly operation.

In the current work, a system is described that uses digital filtering to recover the FECG waveform from low frequency biological noise and associated artifacts. A linear model of the FECG waveform is used to evaluate some 18 different timing intervals of the FECG. The enhanced waveform and accompanying parameters are displayed upon an intelligent graphics terminal to achieve a user friendly operation of the system by clinical staff.

Keywords: Electrocardiography, intra partum monitoring, on-line computer.

Zusammenfassung

Routinemäßiges On-line-Processing des fetalen EGK's
Um sub partu ein fetales EKG routinemäßig on-line verarbeiten zu können, sind folgende Schritte notwendig:
1. Das fetale EKG-Signal muß gefiltert werden.
2. Das gewonnene Signal bzw. die Form des Wellenkomplexes muß mit hoher Präzision gemessen werden, um alle Zeit- und Kurvenabschnitte sowie andere Parameter mit klinischer Bedeutung erfassen zu können.
3. Das fetale EKG und die ausgewerteten Parameter sollen dem Kliniker in verständlicher, einfacher Form zugänglich sein.
4. Die Handhabung und das Processing sollten „anwendungsfreundlich" sein.

Die vorliegende Arbeit beschreibt ein System, daß das fetale EKG digital filtert und so niedrigfrequentes Rauschen und andere Artefakte ausschaltet. Der Herzzyklus im fetalen EKG wird als lineares Modell dargestellt, wobei 18 verschiedene Zeitintervalle ausgewertet werden. Nach Bearbeitung der Signale werden diese sowie die untersuchten Parameter in verständlicher Form graphisch dargestellt und somit „anwendungsfreundlich" für das Klinikpersonal.

Schlüsselwörter: Elektrokardiographie, intrapartuale Überwachung, On-line-Computer.

Résumé

Techniques de traitement de routine en temps réel de l'électrocardiogramme fœtal
Afin de surveiller en routine l'électrocardiogramme fœtal (FECG) au cours du travail, en temps réel, on doit prendre en compte les éléments suivants:
1. Il faut dégager le FECG du bruit de fond.
2. Il faut mesurer le signal obtenu ou tracé avec une grande précision afin qu'apparaissent les durées d'intervalles, les surfaces et les paramètres intéressants pour le clinicien.
3. Il faut que le FECG et les paramètres mesurés soient présentés aux cliniciens de façon significative et simple.
4. Il faut que le controle de la machine et son utilisation soient des opérations d'usage convivial.

Dans le travail actuel, on décrit un système utilisant un filtrage digital afin de récupérer le tracé du FECG au milieu du bruit de fond biologique de basse fréquence et des artéfacts associés.
On utilise un modèle linéaire du tracé du FECG pour l'évaluation de quelques 18 intervalles différents sur le FECG. Le tracé amélioré et les paramètres qui en dérivent sont affichés par une imprimante intelligente afin de donner au système une convivialité pour les cliniciens.

Mots-clés: Électrocardiographie, ordinateur en temps réell, surveillance intra-partale.

References

[1] Cremer M: Über die direkte Ableitung der Aktionsströme des menschlichen Herzens von Oesophagus und über die Elektrokardiogramme des Fötus. MMW 53 (1906) 811
[2] Hon EH, OW Hess: Instrumentation of Fetal Electrocardiography. Science 125 (1960) 553
[3] Rhyne VT: Digital Signal Enhancement of the Fetal Electrocardiogram. Am J Obstet Gynecol 102 (1960) 549
[4] Scott DE: Comparison of Coherent Averaging Techniques for Repetitive Biological Signals. Med Res Eng 9 (1970) 7
[5] Sheild JEA, DL Kirk: The Use of Digital Filters in Enhancing the Fetal Electrocardiogram. J Biomed Eng 3 (1981) 44

D. L. Kirk, B. Sc., A. R. C. S., D. I. C., Ph. D.
Department of Electrical and Electronic Engineering
The University of Nottingham
University Park
Nottingham NG7 2RD, U. K.